Semiconductor Lasers and Fiber Lasers for Fiber-Optic Telecommunications

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Abstract The performance characteristics of semiconductor lasers for fiber telecommunication systems will be reviewed. Modulation speed, intensity noise, single-frequency line width, and tunability are addressed. In addition, recent results concerning the same characteristics in single-frequency, tunable, fiber lasers are reviewed and compared with the semiconductor laser.

Introduction

Semiconductor lasers have now found their way into several large commercial markets. Brightness, diffraction-limited spot size, power efficiency, reliability, and cost per component are the overriding concerns in most of these applications. This includes laser printers, compact disc players, and their use as solid-state laser pump sources. A sole exception is their application to fiber-optic telecommunication systems. Research and product-development activities in this area continue to set impressive device performance records concerning spectral purity, tunability, modulation speed, and relative intensity noise levels. As a result of this effort commercial semiconductor lasers are nearly ideal in terms of their physical properties. Their intensity noise spectra and short-term frequency stability are governed almost exclusively by quantum mechanical effects. The tuning range in monolithic devices has recently been extended to encompass most of the available semiconductor gain band width, and direct modulation speed has entered the millimeter-wave band.

In parallel with the above developments that emphasize their use as sources and local oscillators, the rapid development of travelling-wave optical-fiber amplifiers based on the rare-earth impurity erbium has created a new role in fiber systems for the semiconductor laser. As early as 1964 Koester and Snitzer demonstrated the first traveling wave amplifier as well as fiber laser based on neodymium doped glass [11]. It was not until 1985, however, that experiments by researchers at Southampton University ignited new and sustained interest in rare-earth doped fibers (in particular, erbium-doped fibers)

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as a viable and practical amplification medium [2]. Central to the success of these remarkable amplifiers has been the ability to efficiently pump erbium-doped fiber at wavelengths attainable with semiconductor lasers. In particular, 1480 nm pump sources were first available as a slight modification of proven 1500 nm technology, and later strained quantum-well active-layer technology was perfected for pumping at the more efficient 980 nm absorption band [3]. This new strained-layer technology can also be applied to the pumping of other potentially important rare-earth doped systems. Specifically, 1017 nm strained-layer devices have been used to pump praseodymium-doped fiber, which has demonstrated amplification in the important low-dispersion 1.3 micrometer fiber communications window [4].

In addition to new system opportunities that have resulted from erbium-doped fiber amplifiers (EDFAs), the availability of a new and highly reliable amplifying medium has stimulated work on a new class of laser oscillators that employ EDFAs. Early examples of oscillation by erbium fiber amplification were simple Fabry-Perot resonator devices in which oscillation (sometimes unintentional) resulted from feedback supplied by cleaved fiber facets [5]. More recently, impressive performance in terms of spectral purity, tunability, and intensity noise levels has been demonstrated in more sophisticated geometry’s [6–8]. Thus, rather paradoxically, the semiconductor laser has assisted in the development of a potential competitor for its more traditional telecommunication applications.

In this article we will review the state-of-the-art performance characteristics of semiconductor lasers and fiber lasers. The underlying physics governing field fluctuations, tunability, and modulation speed will be discussed, and recent measurements will be presented. A comparison between these two very different technologies as concerns their application to fiber systems will be made. Finally, the discussion of semiconductor lasers will focus only on single frequency monolithic devices.

**Semiconductor Lasers**

**Direct Modulation**

Owing to their small size, large gain, and ability to be excited by an electrical current, semiconductor lasers have the ability to be modulated at very high rates. This gives them an enormous advantage over any other source technology for application to fiber optic systems. Direct modulation speed in a semiconductor laser is limited by both chip parasitic effects as well as the basic physics of electron-hole stimulated recombination. The equivalent circuit model of the laser chip in Fig. 1 illustrates the important parasitic influences in these devices [9]. The active layer is shown as the impedance Z, and the contact layer capacitance and resistance as well as the depletion-layer capacitance and bond-wire inductance are also illustrated. In practice, the $RC$ time constant associated with the contact layer is most often the limiting parasitic effect. The use of semi-insulating substrates, however, can greatly reduce this effect [9]. In this case devices are limited by the basic physics of electron-hole interaction with the lasing field. This interaction causes a small-signal modulation response function that has a frequency dependence characteristic of a second-order low-pass network [9]. Its form is most easily verified using an approach called parasitic-free modulation [10]. In this approach two single-frequency sources are photo mixed in the active layer of a test device to generate harmonic modulation. This form of modulation is immune to parasitic effects at all frequencies. Typical response data are shown in Fig. 2 at three temperatures.

The corner frequency of this response function is called the relaxation oscillation.
Figure 1. Equivalent circuit model for direct current modulation of a laser diode.

Figure 2. Modulation response of a laser diode in absence of device parasitics. Data is measured at three temperatures.
corner frequency, and, in short, wavelength devices it characterizes the useful modula-
tion bandwidth. This corner frequency is given by the geometric mean of two rates: the
differential stimulated recombination rate (i.e., the product of differential optical gain
and photon density) and the cavity loss rate

\[ \omega = \sqrt{g'p/T} \]

In this expression, \( \omega \) is the relaxation oscillation corner frequency in units of radians per
second, \( g' \) is the differential gain, \( p \) is the photon density, and \( T \) is the photon lifetime.
Increased modulation speed can therefore be attained by operation at high power or by
degradation of the passive cavity \( Q \). Additionally, higher differential gain will also in-
crease speed. A simple demonstration of the latter approach is given in Fig. 2. By
operating a device at reduced temperature the thermal broadening of the active layer gain
spectrum is greatly reduced thereby increasing the gain at a given carrier excitation level
and, in turn, modulation speed through its dependence on differential gain. With the
advent of quantum-well lasers, this same idea can be implemented by using lower-
dimensional electronic systems [11]. Indeed, the fastest semiconductor laser devices are
quantum-well devices. In the future, quantum-wire and quantum-dot structures (two-
and three-dimensional quantum-wells) may also be employed to further enhance modula-
tion speed.

In long-wavelength devices another effect also plays an important role in limiting
modulation bandwidth. This goes by the name of "nonlinear gain," and several possible
mechanisms have been proposed to explain the effect [12, 13]. In general, it is observed
that at some power level, the modulation response function in these devices is dominated
by additional damping effects. The response corner frequency ceases to increase with
increasing power as is typical for relaxation oscillation limited behavior. This effect
seems more pronounced in quantum-well devices, and it has been proposed that the
injected carrier capture rate into the quantum-well is the limiting mechanism. Recently
developed quantum-well structures with very high modulation rates indicate that struc-
tures can be engineered to minimize this effect [14].

**Intensity Noise**

At frequencies above a few MHz state-of-the-art semiconductor lasers exhibit intensity
noise that is dominated by quantum effects. There are many different levels from which
to attack the problem of quantum intensity noise in semiconductor lasers. For the pur-
poses of this discussion, it is possible to describe two regimes of laser operation and the
associated noise behavior: a low-power excess-noise regime and high-power shot-noise
regime [15]. The spectral shape of semiconductor laser intensity noise in each of these
regimes closely mimics the direct modulation response function [16]. In fact, one can
view the associated noise spectra as the laser’s response to various random modulation
sources internal to the device. The most significant of these at low power is spontaneous
emission. This source of noise is fixed above threshold, and its effect on power fluctua-
tions of the lasing mode diminishes inversely with the photon number in the lasing
mode. Hence, for low-power operation the noise power detected into a finite bandwidth
varies inversely with device output power. In this regime the fluctuations can be thought
of as a random signal superimposed on the amplitude of the optical carrier. In particular,
attenuation has the same effect on the noise power and signal power in this regime. It is
for this reason that noise spectral density is often given in terms of RIN (relative inten-
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density noise). This concept is useful so long as RIN is invariant with respect to attenuation. As discussed below, this is only true for operation in the excess noise regime.

At higher power levels, spontaneous emission noise becomes insignificant and the actual quantum nature of the optical carrier (i.e., photon shot noise) determines the noise level. Detected noise power into a given bandwidth rises linearly with output power in this regime. An intensity noise measurement on a strained quantum-well distributed Bragg-reflector device is shown in Fig. 3. Both the excess noise and shot noise regimes are easily seen in the figure. Also displayed is an actual measurement of the shot noise floor (sometimes called the standard quantum limit). For comparison a theoretical intensity noise versus power curve is also displayed for both the laser noise and shot noise levels (solid curves). It is crucial when working in the shot noise regime to have an accurate calibration of this fundamental level. The only unambiguous method for establishing this floor is to use a balanced homodyne receiver (BHR) as diagrammed in Fig. 4. By a simple change of the circuit configuration used to add or subtract photo currents in the BHR, one is able to measure either shot noise (subtraction) or the signal noise level (addition) [17].

The particular device measured here exhibited a noise level as low as 0.8 dB above the shot noise floor at an output power of 10 mW. It is important to note that the actual noise level measured at the BHR was much lower than this (see jagged solid curve in Fig. 3). 0.8 dB is the noise level at the laser facet and accounts for the effect of attenuation between the laser and the BHR [15]. Attenuation in this regime affects noise in a less straightforward way than in the excess noise regime, because shot noise cannot be thought of as a signal. An ideal shot-noise limited optical beam would exhibit a detected photo current noise power that would vary linearly with attenuation as opposed to quadratically for an excess noise limited beam. In general, a beam exhibits neither pure excess noise or pure shot noise, and the effect of attenuation on the noise level lies between these two extremes.

Figure 3. Theoretical and measured intensity noise power versus device output power.
In view of the above, RIN is no longer invariant with respect to attenuation in the shot noise regime. Despite this fact, it continues to be used for historical reasons. For completeness, intensity noise in RIN units for the same measurement is displayed in Fig. 5. We also show the actual RIN at the laser facet resulting from deconvolving loss from the BHR measurement.

**Single Frequency Line Width**

The fundamental line width of single frequency semiconductor lasers is of considerable importance in systems that utilize phase sensitive detection techniques. The principal source of spectral broadening in these devices is spontaneous emission. Spontaneous photons added randomly to the lasing field create a phase diffusion of the lasing field phase. This diffusion gives the mode spectrum its Lorentzian line shape. The line width at half power varies inversely with power in accordance with the modified Schawlow-Townes formula. As with intensity noise this power dependence reflects the decreasing significance of the fixed spontaneous emission rate with increasing photon number in the

![Figure 4. A balanced homodyne receiver for shot noise calibration and laser intensity noise measurement.](image-url)
lasing mode. A significant additional modification of the Schawlow-Townes formula was recognized as important [16, 18] in the early 1980s. This work built on earlier work by Haug and Haken showing that detuned operation of a laser oscillator creates amplitude-phase coupling of the lasing field. This coupling, in turn, creates an additional channel for spontaneous noise to couple into the field phase and thereby enhance the line width. The effect is very large in semiconductor lasers and can enhance line width by as much as a factor of 40 [19]. Devices having cavity lengths of approximately 300 microns and with uncoated facets exhibit line-width power products in the range of 50 MHz mW.

Several methods for reducing line width are apparent from observation of the fully modified Schawlow-Townes line width formula

$$\Delta \omega = \frac{S}{2P} (1 + \alpha^2)$$

In this expression $S$ is the spontaneous emission rate, $P$ is the number of photons in the lasing mode, and $\alpha$ is the so-called line width enhancement factor, which characterizes the strength of the amplitude-phase coupling effect [16, 18, 19]. Enhanced facet reflectivity and longer device cavity lengths are both effective ways to reduce line width by increasing the cavity $Q$ (i.e., decrease threshold $S$). Quantum-well active layers can also be tailored to reduce the $\alpha$ parameter to values as small as $-1$ ($\alpha$ is typically $-4$ to $-5$ in bulk material).

In addition to spontaneous emission, semiconductor laser line width is also influenced by a number of other less fundamental effects. These effects become significant at high power levels where the line width can saturate at a power independent value. For many years a variety of mechanisms thwarted the best efforts of researchers to narrow the line width of solitary semiconductor lasers below 1 MHz. In DFB devices longitudinal variations in modal intensity caused by the DFB mechanism were eventually linked to this high power line width. The resulting spatial hole burning of the gain medium can be suppressed by use of very long cavities. Intensities in these cavities for a given modal photon number are lower than for shorter cavity devices thereby reducing the spatial

Figure 5. RIN versus laser power for device measured in Fig. 3. Noise at laser output facet is also displayed.
hole burning effect. By employing long cavity devices in this way and by using quantum-well active layers as described above high power line widths as narrow as 50 kHz have been demonstrated in solitary devices.

Before leaving this subject we mention an interesting and potentially useful link between phase and intensity noise in these devices. As mentioned above, the $\alpha$ parameter gives a measure of amplitude-phase coupling in the semiconductor laser. Its effect on noise is normally considered undesirable. However, recently we have shown that the correlations between the field amplitude and phase that are created by the alpha coupling can be used to decrease SL intensity noise [20, 21]. In an approach we call amplitude-phase decorrelation, information about intensity fluctuations that is stored on the field phase is used to damp intensity fluctuations in a simple passive process. Power noise reductions as large as 14.5 dB have been demonstrated using this approach [22].

**Wavelength Tunability**

The amplitude-phase coupling responsible for line width enhancement results from a carrier density dependent component of refractive index in the SL active layer (i.e., gain spectrum detuning). Although undesirable for narrow line width operation, this effect provides a convenient means to electrically tune the wavelength of a semiconductor laser. Wavelength tunability in these devices involves great fabricational sophistication. Impressive results have been demonstrated by groups in Japan and at AT&T using Bragg grating devices having three contacts to allow independent phase control, grating phase control, and gain control [23–25]. Seamless tuning over wavelength spans of nearly 10 nm has been demonstrated. A physical limitation on tuning in these devices, however, is the magnitude of the alpha parameter in semiconductor active layers. Until recently it seemed that direct electrical tuning would be limited to the ranges already established. Workers at AT&T, however, have demonstrated electrical tuning over 57 nm (not seamless) using a novel Bragg wave guide coupling approach [26]. Rather than basing wavelength control on a Bragg grating operating in the reflection mode, these new devices use a Bragg grating to couple two parallel waveguides within the same laser chip. Since the coupling involves a smaller differential wave vector to link modes in each guide, a larger tuning range is possible using the same amount of carrier induced index change.

**Fiber Lasers**

**Overview**

Although they are relatively new in comparison to semiconductor lasers, fiber lasers have evolved very quickly. Beginning with the first simple demonstration of oscillation the field has seen a variety of more sophisticated approaches that have used both ring and Fabry-Perot geometries. Broad band tunability with limited frequency stability in a ring geometry was demonstrated by groups at Bellcore and at NTT [6, 27, 28]. The NTT group used a discrete interference-filter element that was rotated with respect to the fiber axis to achieve tuning. Bellcore demonstrated a novel liquid-crystal birefringent filter as well as a surface acoustic wave filter. Researchers at United Technologies Corporation recently demonstrated a single frequency Fabry-Perot geometry that incorporated newly developed fiber Bragg filters for mirrors [7]. This approach is very elegant since no discrete components are required and lasing action occurs entirely within the fiber. We have recently developed the first single-frequency, ring-geometry fiber laser with long term frequency stability [8]. In our approach we have employed for
the first time fiber-optic Fabry-Perot Filters (FFP) as frequency selective elements. These filters use a short section of single-mode optical fiber as the resonant cavity for the filter [29]. A dielectric stack at the ends of the fiber creates a high finesse and tuning is accomplished by varying the length of the fiber (0 to 15 volts supplied to a piezoelectric element normally scans one free-spectral-range of the device). Our single-frequency ring uses two FFP filters to achieve frequency stability as well as wide wavelength tunability. Its operation and characteristics will be detailed in the next section. Before proceeding, however, it is important to note that the field of fiber lasers is very large. For the purposes of this discussion only a narrow subset of that field, namely, single-frequency tunable fiber lasers, will be addressed here. For a broader overview of this subject, the reader is referred to [32] and the references therein.

**A Single-Frequency, Widely-Tunable, Fiber Ring Laser**

Figure 6 illustrates the components used in the ring laser. The 980 nm output of a titanium:sapphire (or a diode laser) laser was coupled through a wavelength division multiplexer for the pumping source. A pigtailed polarization-dependent isolator (isolation 35 dB) was used to prevent spatial hole burning caused by bidirectional operation for more stable single frequency operation. The isolator also served to block feedback from the output port of the system. A polarization controller (PC) was used to match the polarization state to the input polarization of the isolator. The coarse wavelength selective element was a broad band fiber Fabry-Perot (FFP) filter with a 26.1 GHz (0.196 nm at 1.5 microns) bandwidth (FWHM) and a 4020 GHz free spectral range (FSR). A second, frequency stabilizing fiber Fabry-Perot is shown as FFP (NB) and will be discussed momentarily. The total cavity loss (without the second Fabry-Perot) was estimated to be less than 6.5 dB from a small signal gain measurement and threshold data. The specific sources of loss were 2.5 dB from the FFP, 1 dB from the isolator, 1 dB from the wavelength division multiplexer and coupler, and 2 dB from mode mismatch and splice losses between the erbium fiber and other devices. The threshold was approximately 10 mW. The cavity length was 30 meters corresponding to a free spectral range (FSR) of 6.6 MHz for the laser.

The laser output was coupled to a 50/50 coupler at 1550 nm to enable simultaneous monitoring of the lasing spectrum using both a high resolution scanning Fabry-Perot

![Figure 6. Schematic of single-frequency, tunable erbium ring laser showing broad band (BB) and narrow band (NB) fiber Fabry-Perot filters (FFP).](image-url)
interferometer and a grating monochromator to determine the lasing wavelength. Tuning was possible by changing the voltage on the FFP, thus scanning the center frequency of FFP over a different longitudinal cavity mode of the ring laser. Tuning over 30 nm (corresponding to the FFP filter FSR) between 1530 nm to 1560 nm was possible by applying 0 to 17 DC Volts (see tuning curve in Fig. 7). The tuning range is believed to be limited only by the FSR of the FFP filter. After 17 Volts, it retraced the wavelength at zero applied Voltage. Single frequency operation was observed for periods as long as several seconds, although there existed mode hopping under an envelope on the order of 1 GHz, presumably due to cavity instabilities from thermal drift and acoustic noise. Frequency stability was better when using a diode laser pump. We attribute this to gain fluctuation in the erbium fiber due to the pumping source frequency fluctuation, which was more evident in our titanium:sapphire laser. Threshold pump power was between 8.8 mW and 10.4 mW over the entire tuning range. Gain shaping with an additional filter could be applied to further reduce the variation [30].

To suppress mode hopping, the second narrow band width FFP (1.39 GHz, 0.01 nm at 1550 nm, insertion loss 2.5 dB maximum) was placed in the cavity. The measured threshold pumping power was around 14 mW with the tandem FFP configuration. To prevent interetalon interactions, a polarization-independent isolator was introduced between the two FFP filters. These interactions were observed to produce additional mode hopping. With the isolator in place, the resulting transmission function from this tandem FFP filter can be considered as the product of two independent transmission functions of

![Figure 7. Tuning versus voltage applied to fiber Fabry-Perot filter.](image)
FFP filters. Tuning was possible over the entire gain spectrum with 1 nm intervals corresponding to the FSR of the smaller band width FFP. Mode hopping was completely suppressed. Instead, the lasing mode was observed to slowly drift until, after several minutes, oscillation would jump to an adjacent longitudinal mode.

Figure 8 shows a lasing spectrum taken using the scanning Fabry-Perot Interferometer (Newport Research Super-Cavity SR-170. FSR 6 GHz.). This device has a resolution of 1 MHz, which is sufficient to resolve the 6.6 MHz FSR of the ring laser longitudinal modes. The side mode suppression ratio was measured by detecting the ring laser output using a high frequency photo diode and then analyzing the photo current using a microwave spectrum analyzer. The measured side mode suppression was higher than 35 dB. Later, we also used another fiber Fabry-Perot with a smaller band width (125 MHz). This produced a side-mode suppression ratio no smaller than 48 dB. A plot of measured side-mode suppression versus tuning is presented in Fig. 9.

The intensity noise of this device was measured using the balanced homodyne approach described above. In erbium doped fiber lasers, one expects a relaxation oscillation frequency on the order of 10 kHz due to the relatively long fluorescence lifetime of erbium [31]. Beyond this frequency, fluctuations in pump power are strongly damped, and the intensity noise power should be dominated by spontaneous emission. The measured noise power (near 310 MHz) showed linear dependence on the output power that was 8.5 dB above the shot noise level. Data showing both laser noise and the shot-noise floor versus output power are given in Fig. 10.

**Conclusion**

State-of-the-art semiconductor lasers are nearly ideal optical sources. In addition to being reliable and compact, they are low noise, exhibit narrow line widths, and are widely tunable with small applied currents. They are unique among all laser devices in offering the enormous benefit of efficient, high speed, direct current modulation. There
is little chance that any other source will ever supplant the semiconductor laser in fiber optic telecommunication systems.

Fiber laser sources, however, despite being incapable of direct modulation, have several advantages of their own over semiconductor devices. The greatest of these is the fact that light generation occurs in the fiber and must never leave the fiber en route to the transmission cable. Packaging related problems are therefore greatly reduced in such a device. (Although one could argue that the packaging of a semiconductor laser still plays a role here except now moved back one level to the optical pump diode.)

In terms of other performance figures of merit, fiber lasers, despite their brief

**Figure 9.** Measured side mode suppression ratio versus tuning in the ring laser.

**Figure 10.** Intensity noise power of erbium ring laser versus laser output power measured relative to shot noise power floor using the balanced homodyne method.
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Table 1
A Comparison of Semiconductor Laser and Fiber Laser Characteristics

<table>
<thead>
<tr>
<th>Property</th>
<th>Semicond. Laser</th>
<th>Fiber Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod. speed</td>
<td>28 GHz</td>
<td>25 GHz (ext)</td>
</tr>
<tr>
<td>Power noise</td>
<td>Shot limited</td>
<td>Shot limited</td>
</tr>
<tr>
<td>SMS</td>
<td>50 dB</td>
<td>50 dB</td>
</tr>
<tr>
<td>Tunability</td>
<td>50 nm</td>
<td>50 nm</td>
</tr>
<tr>
<td>Linewidth</td>
<td>50 kHz</td>
<td>&lt;1 kHz</td>
</tr>
<tr>
<td>Mode-locking</td>
<td>Difficult</td>
<td>Easy</td>
</tr>
</tbody>
</table>

development history, are nearly as good or exceed the performance of state-of-the-art semiconductor devices. As shown above, intensity noise levels in the ring device that we developed are within 10 dB of the standard quantum limit and can probably be reduced to a few dB above this level. For comparison, state-of-the-art semiconductor lasers operate close to this level. Single-frequency line width in solitary semiconductor lasers has only recently been reduced to values around 50 kHz in specialized structures. For comparison the first fiber ring sources had line widths of less than 10 kHz. Another important property of telecommunication sources is high side mode suppression (SMS). Side mode suppression in the best DFB devices exceeds 60 dB. Typically only 30 dB SMS is required in digital systems and 60 dB is reserved for analog transmission such as in proposed cable television links. To date, the only reported data on SMS in tunable all-fiber sources is by our group for the ring device discussed above. It has an SMS of 48 dB, which could potentially be increased to nearly 60 dB with minor modifications now under way.

Finally, as discussed above, wavelength tunability in semiconductor lasers involves extraordinary fabricational sophistication. The tuning range demonstrated in the Caltech single frequency ring is 30 nm (limited by the tuning filter; 50 nm should be possible with a new filter). While this tuning involves mode hopping between modes separated by 6 MHz, we believe seamless tuning, if needed, could be accomplished over the same range by introduction of a phase control element into the ring.

Some of the above characteristics are summarized in Table 1. Modulation speed for the case of the fiber laser is given assuming an external modulator. The category mode-locking covers both active and passive approaches and was not addressed in the above discussion. Also omitted has been the use of fiber lasers for generation of soliton pulses [32]. This latter topic is potentially one of enormous importance in long-haul fiber systems.

It is too soon to make any predictions concerning the possible future role, if any, of fiber lasers in telecommunication systems. However, their performance characteristics to date are impressive despite a much shorter and smaller cumulative development effort than that seen in the past decade for semiconductor lasers.

Note: The authors have recently demonstrated an erbium oscillator with a shot-noise limited intensity noise spectrum (see reference 33). In addition, more complete data on the ring oscillator line width appears in reference 34.
References